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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Semiconductor Measurement Technology:

Optical and Dimensional-Measurement Problems With Photomasking in Microelectronics

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Semiconductor Measurement Technology:

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PREFACE

This study was carried out in the Optical Physics Division as a part of the Semiconductor Technology Program in the Electronic Technology Division at the National Bureau of Standards. The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. The Program receives direct financial support principally from three major sponsors: The Defense Advanced Research Projects Agency (ARPA), The Defense Nuclear Agency (DNA) and the National Bureau of Standards. The specific work reported herein was supported by ARPA.*

During the conduct of this study, particularly strong statements were received from the integrated circuits industry emphasizing the critical need for the development of NBS line width standards in the 1-μm range to assist the industry in meeting the micrometrology requirements associated with high resolution photomasks. These statements included an emphasis both on the need for NBS traceability in this field by small mask making establishments in their marketplace interactions with larger organizations and Government and on internal needs of semiconductor device manufacturers in connection with productivity problems. In response to the needs disclosed and defined in this study, a two-year project, jointly funded by ARPA and NBS, was initiated to develop a 1-μm line width standard through implementation of the recommendations of this study.

Special acknowledgement is gratefully made to Dr. Donald B. Novotny, Semiconductor Processing Section, Electronic Technology Division, NBS, for his considerable assistance in the study described in the present report. This assistance included, in part, participation in the visits to photomask and IC facilities, gathering and analyzing information from the open literature, participation in technical discussions with representatives from the IC industry, and helpful suggestions in the preparation of this report.

*Through ARPA Order 2397, Program Code 4D10.

OPTICAL AND DIMENSIONAL-MEASUREMENT PROBLEMS WITH PHOTOMASKING IN MICROELECTRONICS

BY

JOHN M. JERKE

Abstract: Photomasks are the basic artifacts for transferring design geometry to the semiconductor wafer in integrated circuit (IC) production. Currently, photolithographic techniques using optical equipment are the primary means for both fabricating masks and using masks to print patterns on wafers. The present study was to identify the major optical and dimensional-measurement problems related to the fabrication and use of masks.

The results show that the primary optical problems are those related directly to the use of optical instruments for dimensional measurements of IC pattern geometry. Furthermore, most suppliers and users of optical equipment for mask fabrication do not conduct sufficient optical testing to determine imaging performance. The basic limitations derived from light diffraction and coherence continue to limit the quality of masks and IC devices with sub-micrometre geometry, and acceptable units are produced generally on a best-effort basis. The primary dimensional-measurement problems are (1) accurate measurements below about 10 μm, (2) edge definition or location of a physical edge for a line, and (3) mask registration. Recommendations to improve the accuracy of dimensional measurements are given.

A bibliography of publications related to the optical and micro-metrological aspects of photomasks is included.

Key Words: Integrated circuits; microelectronics; micro-metrology; photolithography; photomask; semiconductor technology.

1. INTRODUCTION

Photomasks are fundamental to the processing of integrated circuit (IC) devices since the mask serves as the basic pattern for transferring the design circuit geometry to the semiconductor wafer. A photomask is essentially a repeated array of microphotographs of circuit patterns produced by photolithographic techniques onto a glass substrate. Optical systems operating in the visible spectrum are presently the primary means used to transfer both the design artwork to the mask and the resulting mask pattern to the semiconductor wafer. Estimated yearly sales of photomasks by independent U. S. suppliers are currently between $20 million and $25 million; these figures do not include in-house production of photomasks by IC manufacturers, nor do they provide an indication of the immense importance of photomasks to the electronics industry and its customers.

As reported widely in the technical literature [1-6], the IC industry has continued to encounter significant measurement and optical problems related to the manufacture and use of photomasks in semiconductor processing. Many of these measurement and optical problems have persisted since the early development of IC's around 1960. These problems are becoming increasingly significant with the present and future needs for higher density, more complex circuitries, larger plate geometries, and devices requiring tight dimensional tolerances on line widths in the micrometre region and below. A study concerned with major measurement problems in process and assembly control of IC devices [7] indicates that existing dimensional measurement and optical problems related to photomask technology also appear to affect adversely device yield and reliability.

The primary objective of the present study was to identify the major measurement and optical problems related to the manufacture and use of photomasks in semiconductor processing. This study included a preliminary technical investigation of selected photomask problems and drawing up recommendations for approaches to meeting the existing measurement and optical needs of the IC industry. The study was a joint effort between the Optics and Micrometrology Section and the Electronic Technology Division of the National Bureau of Standards and was supported by the Defense Advanced Research Projects Agency (ARPA) as part of the major program on Advancement of Reliability, Processing, and Automation for Integrated Circuits with the National Bureau of Standards (ARPA/IC/NBS) [7]. In addition, results relating to measurement and optical problems that were obtained from a concurrent program conducted by the U. S. Atomic Energy Commission/Lawrence Livermore Laboratory (LLL) [8] for ARPA/IC/NBS to study automated photomask-inspection procedures are selectively presented in this report. Under the present study, NBS personnel were joined by LLL personnel in some of the field visits to photomask, IC, and instrument manufacturers.

Appendix A by Fred W. Rosberry (NBS) presents experimental data from wire-diameter measurements made with both filar and image-shearing eyepieces attached to a microscope. These microscope eyepieces are widely used throughout the IC industry to make dimensional measurements on photomasks. Appendix B by Richard E. Swing (NBS) discusses the effects of the degree of coherence of the illumination source on the apparent position of physical edges in such instruments as microscopes and microdensitometers. Measurements of line widths, oxide windows, and other circuit geometries are routinely made by photomask suppliers and IC producers using optical equipment under various degrees of illumination coherence. Appendix C is a selected bibliography of photomask publications.

2. BACKGROUND

The basic approach to photomask fabrication is photolithography with optical instruments operating in the visible spectrum. In addition, non-optical techniques such as electron-beam [9] and X-ray lithography [10] are currently being used, on a limited scale, for mask fabrication. A master mask with an array of primary patterns is shown in figure 1. This mask includes a wide range of test, continuity, and alignment patterns used during the fabrication process.

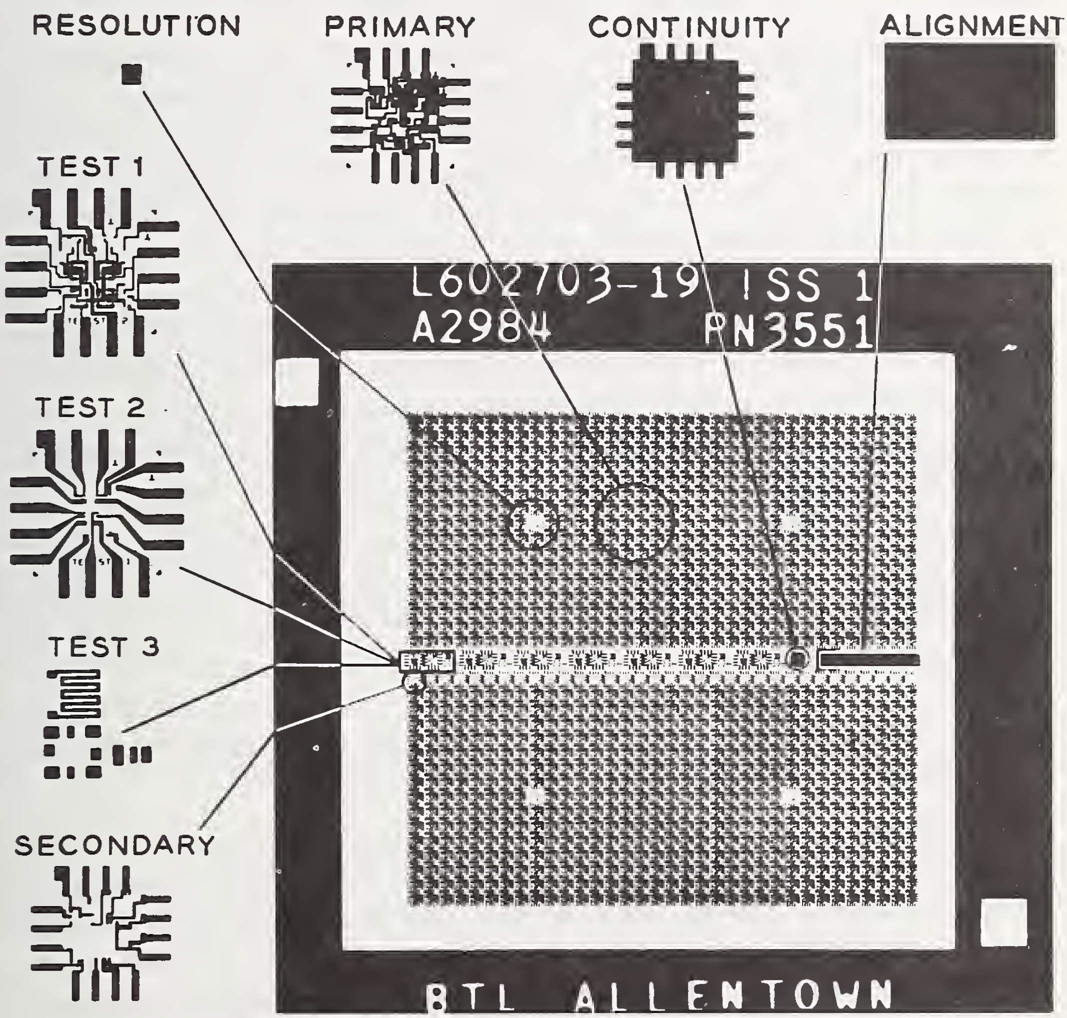

Figure 1. An integrated-circuit photomask and its various patterns. (Reprinted with permission from The Bell System Technical Journal. Copyright 1970, The American Telephone and Telegraph Company.)

BACKGROUND

The procedures used to manufacture photomasks are not widely standardized throughout the IC industry, although there are basic steps common to mask fabrication for silicon devices. These steps are illustrated schematically in figure 2 and include the following: (1) pattern generation; (2) stepping the pattern over the photoplate; and (3) photoprinting the master onto the working mask.

The first step, pattern generation, is the transfer of the design information to a glass plate or master reticle with a pattern size typically ten times that to be printed on the silicon wafer. This transfer may be accomplished directly by a computer-controlled pattern generator or, as shown in figure 2, by photographically reducing artwork that previously has been cut from plastic film. A photographic reduction of 20X to 100X is generally used and for larger reductions involves two or more reductions. In the second step, the master reticle is placed in a step-and-repeat camera which produces multiple exposures of the same pattern on another glass plate. The pattern reduction for this step is generally 10X and, depending upon the size of the production wafer and the chip area, several hundred to several thousand repeat patterns may be printed on the resulting master photomask. In the third step, the master photomask is contact printed to form a sub-master, and the sub-master, in turn, is contact printed to give a working mask. All masters are generally inspected for defects, and for hard-surface masks, most of the sub-masters and working masks are also inspected. In addition, critical-dimension measurements are made on several selected areas of the mask patterns; all masters and from 10 to 25 percent of the working masks are measured.

The master photomask is usually photographic emulsion on glass. Although emulsion on glass is also used frequently for the sub-master and working masks, the use of hard-surface masks consisting of chromium on glass and iron oxide on glass is increasing significantly. The working masks are commonly 6.3 cm x 6.3 cm (2 1/2 in. x 2 1/2 in.) and 7.6 cm x 7.6 cm (3 in. x 3 in.); the use of masks measuring 10 cm x 10 cm (4 in. x 4 in.) is increasing with adoption of the 7.6-cm (3 in.) diameter silicon wafer.

The working masks are used as negatives, or stencils, to expose a thin layer of photoresist previously coated on a semiconductor wafer. After a sequence of development, chemical etching, and sometimes impurity diffusion, this entire procedure is repeated with as many as twenty different masks for the same wafer. Therefore, each mask must register precisely with the wafer patterns produced by the previous masks. The resulting wafer contains many repetitions of the desired IC and is subsequently diced.

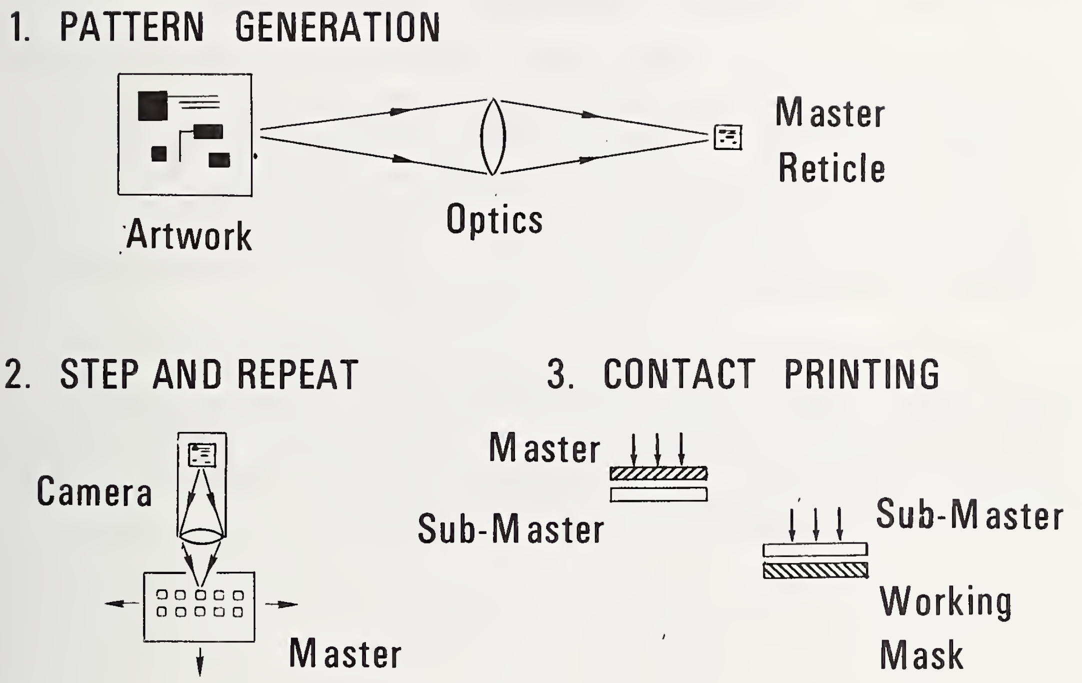

Figure 2: Basic steps of photomask fabrication.

3. APPROACH

The major effort to identify the measurement and optical problems associated with current photomask technology consisted of a literature search and field visits to photomask, IC, and instrument manufacturers and research organizations. The additional technical investigations of measurement and optical problems discussed in appendices A and B were selected on the basis of information gathered during the early phase of the study. Attendance by NBS personnel at four meetings of the American Society for the Testing of Materials (ASTM)/Committee F-1 on Electronics* afforded additional contact with the IC community and the opportunity to participate in discussions of measurement and optical problems.

The sources for the literature survey included the NBS library and computer-aided literature searches. The computerized searches were obtained from the following organizations: (1) National Technical Information Serviee (NTIS), Springfield, Va.; (2) Smithsonian Scientific Information Exchange (SSIE), Washington, D. C.,; and (3) Defense Documentation Center (DDC), Alexandria, Va. Selected literature was obtained and reviewed. A bibliography of publications pertinent to the present study is given in appendix C.

The field visits by NBS personnel included four photomask suppliers, three research organizations, seven equipment manufacturers, and eight IC producers. Most of the IC producers had in-house mask-making facilities. On-site technical discussions were held with industry personnel. Generally, a plant tour of mask-fabrication and mask-inspection facilities was included.

*Meetings at Palo Alto, Ca. (Sept. 6, 1973), New Orleans, La. (Jan. 15-16, 1974), Gaithersburg, Md. (June 12, 1974), and Scottsdale, Ariz. (Sept. 5, 1974).

4. RESULTS AND DISCUSSION

The present study reveals that significant dimensional-measurement and optical problems exist throughout the IC industry in the manufacture and use of photomasks. The relative importance of these problems to the various segments of the IC community depends primarily on the function and services of the particular facility, i.e., photomask supplier, IC producer, or instrument maker. The present discussion of these problems does not reflect any particular ordering of importance; this discussion treats in depth only those problems of widespread significance in the IC industry.

4.1. Optics

Although the present study includes the broad use of optics in photomask technology, the major optical problems were found to be unrelated directly to the photolithographic processing of photomasks. Instead, these optical problems are related to the existing measurement problems through the optical systems used for photomask measurements. Therefore, these optical problems will be discussed under the following section on measurement problems.

Several current observations that may not be regarded specifically as major optical problems do warrant a separate discussion in this section. First, the basic limitations imposed by diffraction and partial coherence on the formation of optical images have obviously not changed despite improvements in such areas as photolithographic process controls, photoresist resolution, and mechanical precision of optical instruments. These limitations have been acknowledged repeatedly in the technical literature by workers in the IC field [11-14] and were known to optical and microphotographic specialists prior to IC development [15-18]. A study of image formation by visible radiation passing through simple geometrical apertures, without the additionally degrading effects of lenses, mirrors, and windows, will show the following: photolithographic techniques cannot provide photomasks and IC devices with good dimensional fidelity for geometrical elements comparable in size to the wavelength of light (about 0.4 μm to 0.7 μm). Linewidths of these dimensions have been produced with uv-visible radiation and deformable photomasks which apparently reduce diffraction effects [19]; this processing technique is currently not adaptable to production methods. For geometry smaller than about 1 μm, the effects of illumination coherence [20] on image formation become significant and must be considered by users of optical instruments as discussed later. In any event, a technology using radiation of shorter wavelengths than visible radiation appears necessary to provide high quality photomasks and IC devices with pattern dimensions well below about 1 μm. Electron-beam and x-ray lithography are possible considerations that presently exist on a developmental basis.

Secondly, the purchase and use of optical equipment without either specific optical test data furnished by the instrument manufacturer or optical acceptance tests by the user is common practice. Consequently, optical instruments are used for fabricating small dimensional geometries on photomasks and IC devices without adequate information about the performance capabilities of the optical system. The absence of optical testing is not limited to the IC community; although, the large percentage of capital investment in optical equipment and its extensive use by this industry dramatizes this deficiency. One reason for this absence of test data is that optical components mounted in photolithographic instruments do not usually lend themselves to isolated testing. Optical performance is governed by such fundamental properties as the pupil function (wavefront error), the optical transfer function (OTF), resolution, depth of focus, and the presence of aberrations. These properties can be obtained by interferometric lens testing [21, 22] prior to mounting the lens in the system. In the absence of such testing, the quality of photomasks and IC devices is limited by an unknown factor of optical performance.

Finally, it should be noted that some U.S. and foreign optical companies have responded to the needs of the IC industry by providing optical systems specifically designed for photomask and IC processing. Such systems include minimum image distortion over large fields, lens-aberration corrections for the wavelengths of the light used to expose emulsions and photoresists, and materials which are dimensionally stable within the operating environment. It should be noted that small-volume IC equipment manufacturers generally do not have the financial means to have these special lenses designed and cannot guarantee a sufficient market to assure the lens manufacturer the recovery of design and manufacturing cost. Therefore, optical components in some photomask and IC processing equipment are sometimes off-the-shelf items that were designed for other purposes and constitute a strong compromise in performance and cost.

4.2. Dimensional Measurements

Photomask and IC producers are generally operating within the same technology for dimensional micromeasurements that has existed since the early development of IC's around 1960. Basically, this approach is a human operator collecting visual readings through a microscope fitted with a micrometer stage or measurement eyepiece. As photomask and IC patterns have approached 1-μm line widths, these optical measurements have involved larger discrepancies and errors. As in the past, most photomask and IC producers have continued to rely on commercially available instruments to satisfy their measurement requirements. Only a few IC facilities with research and development capabilities have developed any in-depth programs to address their own particular measurement needs.

Generally, the approach adopted by the instrument manufacturer to the increasing micromeasurement problem is to improve the mechanical repeatability, or precision, of the equipment and to replace visual observations and manual operations with automation and electronics. This approach is necessary for improved measurement precision, but is not sufficient to obtain the accuracy that is needed for measurements approaching 1 μm. However, it is important to note that existing optical measurement equipment could be used satisfactorily for accurate measurements down to about 1 μm under the following conditions: (1) knowing the operation limitations and error values with different types of illumination and samples; and (2) calibrating the system with a material length standard, or artifact, that is directly related to the standard unit of length.

One attitude adopted by some IC producers has been to assume that dimensional-measurement problems can be tolerated provided that the final IC device performs satisfactorily. This approach may be costly and time consuming by requiring the producer to test each IC device and to select as acceptable only those devices meeting performance specifications. Since the manufacture, inspection, and use of photomasks occur early in semiconductor processing, it appears far more desirable to detect defects, including dimensional errors which would lead to device failure, in these front-end processes rather than at the final test station. With early inspection techniques, the unit cost of the surviving devices can be much lower; moreover their reliability will be improved, and the ultimate yield can be increased significantly since the photomask is a pattern for many individual devices. Of course, photomask inspection is routinely performed in current IC processing in order to achieve these desirable objectives. However, such inspection is of little value if existing measurement difficulties or limitations lead to dimensional-measurement inaccuracies and eventual device rejection or failure.

The major dimensional-measurement problems associated with photomask technology in the IC industry can be grouped into the following categories: (1) measurement of small dimensions in the micrometer and submicrometer range; (2) edge definition or location of a physical edge for a line; and (3) registration, or relative alignment, of several photomasks used to form successive patterns on a single wafer. The common manifestation of these problems appears in the optical instruments used to fabricate, inspect, and register photomasks. Therefore, as mentioned earlier, the following discussion of these specific measurement problems will include the related optical problems.

4.2.1. Measurement of Small Dimensions

As noted earlier, dimensional measurements are routinely made on photomasks to determine if design dimensions have been held within tolerances during mask processing. These measurements are generally line-width measurements made on several different parts of the circuit geometry. Selection of these measurement areas is made during preparation of the initial photomask artwork. It is only necessary to make these measurements at specified locations over the entire mask because measurement errors are essentially not randomly distributed. These measurements should be made on different line widths at different locations to account for variations in optical quality over the exposure field of the instruments used to print the mask.

Line-width or oxide-window measurements are a length measurement from one edge of the line or window to the other edge of the same line or window. This type of measurement is clearly different from such linear measurements as scale calibrations which are basically line-spacing measurements. To further illustrate this difference, it is noted that the present NBS line standard interferometer [23] for linear-scale calibration provides accurate measurements between centers of adjacent lines or from the edge of one line to the corresponding edge of the adjacent line, but not from one edge to the other edge of the same line. This important measurement difference is generally recognized by the IC community even though linear scales or other line-spacing artifacts, which have been calibrated from line center to line center or from left (right) edge to left (right) edge, are used routinely for line-width measurement calibrations.

Typical critical dimensions for photomask and IC device geometry using conventional photolithographic processing presently range from 2 μm $\pm$ 0.25 μm for low-volume production to 5 μm $\pm$ 0.25 μm for high-volume production. Special devices such as microwave circuitry include 1 μm and submicrometer geometry. These devices are generally produced on a best-effort basis, and the measurement inaccuracy is either unknown, unquoted, or so large that it approaches the nominal dimensions of the patterns. These measurement inaccuracies of $\pm$ 0.25 μm are often desired values rather than values that can be substantiated by relating the measurement to the standard unit of length. Also, these measurement tolerances sometimes include precision tolerances. Precision is usually defined [24] as a measure of the ability to repeat a given measurement, while accuracy is a measure of the difference between a given measurement and the actual or standard value.

It is often suggested that if all masks used to print a wafer are generated in the same system, the precision of mask measurements is all that is required; whereas, if several systems are used, then accuracy, or at least dimensional correlation, is required. As discussed earlier, this conclusion does not stand in view of the desir of many IC producers to predict final device performance by comparing circuit dimensions with design specifications. For this comparison, measurement accuracy must be known.

In another recent study supported by ARPA [25], it was reported that automatic photomask systems commercially available in the U.S. provide the capability for efficient production of photomasks with the levels of accuracy and precision needed for highly reliable devices and yields. However, this report does not point out that this accuracy is attributed to the equipment and not necessarily the generated photomask. The report also does not mention that the equipment accuracy can be assured only if the manufacturer calibrates the instrument by techniques, such as interferometry, that relate to the standard unit of length. In any event, the equipment user is not guaranteed that the accuracy quoted by the equipment manufacturer can be transferred directly to the photomask. Accurate dimensional measurements on the photomask must be provided by an independent method.

The majority of photomask suppliers and users rely chiefly on the optical microscope with the filar or image-shearing eyepiece to perform small dimensional measurements down to about 2 μm. Other microscope systems that are used less frequently include coordinate-measuring systems with translating stages and scanning microdensitometers. More recent developments to reduce human reading errors, measurement time, and visual strain employ electronic interfacing with the optical microscope; these system include automated dimensional readout or a video display with fiducial lines for positioning over the magnified image of the object to be measured. Advertised values of accuracy for these systems range from 0.1 μm to 0.01 μm. It should be stressed that very often precision and accuracy are advertised as being the same value. The quoted error is termed an instrument error or accuracy by the manufacturer when, in fact, the values quoted are the precision. In some cases, the measuring-equipment manufacturer states that furnished linear scales, or micrometer stages, are traceable to NBS dimensional calibration. Other instrument manufacturers quote only the precision and accuracy of mechanical stages or other moving parts, but do not list the accuracy and precision expected with the actual dimensional measurements. Still other manufacturers quote only the instrument sensitivity which is usually the finest divisions on dials, verniers, or gauges.

The filar or image-shearing eyepiece replaces the normal eyepiece in an optical microscope to permit dimensional measurement of objects placed on the specimen stage. The filar eyepiece is basically a crosshair which is moved across the field of view by turning a micrometer drum, and the difference between two drum readings is related to the linear dimension of the object. A shearing eyepiece produces two identical images that are sheared or split by turning a micrometer drum; these two images are often filtered to give a red and green image. The amount of shear, or difference between the drum reading for zero shear with images superimposed and the reading for shear with the two image edges (left edge from one image and right edge from other image) just touching or slightly overlapping, is related to the object length in the direction of shear. Both of these measurement systems require visual judgement to position the crosshair and sheared images even though the readout of the drum settings may be automated as mentioned earlier.

One of these two measurement systems is usually preferred by users at each photomask and IC facility based on their requirements and experience. At some facilities, both systems are used routinely, and the choice for a particular measurement depends on the type of photomask and the measurement conditions. Sample types and measurement conditions used with both the filar and image-shearing systems include emulsion masks with low reflectance, highly reflective chromium masks, semitransparent iron-oxide masks, opaque wafers, transmitted and reflected illumination, and filtered and polychromatic illumination.

Differences between filar and image-shearing measurements of the same geometrical feature on a mask vary from a few percent to over twenty percent throughout the IC industry. These differences most likely stem from the variable measurement conditions and sample types already mentioned as well as other factors such as optical differences and illumination coherence. The effort of some IC facilities to control tightly the measurement conditions results primarily in improved precision on a particular measurement system, but does not eliminate differences between the measurement systems. A preliminary comparison of filar and image-shearing measurements made at the NBS on a nominally 15-μm diameter wire and a 10-μm diameter pinhole was included in the present study. A comparison of line-width measurements on a nominally 12-μm width chromium line on a glass substrate was also included. The results of these measurements are reported in appendix A, and they represent some of the measurement differences typically found between the filar and image-shearing systems.

The primary difficulties associated with dimensional measurements of mask patterns appear to be line-width measurements, unknown accuracies, and operating limitations of the optical-microscope systems used to make the measurements. Line-width measurements require locating the left and right edges of the line. Unless the physical profiles of both edges are identical, differences in edge location can be expected in measurement systems ranging from relatively simple microscopes to sophisticated interferometers. This fundamental measurement problem of edge detection is discussed further in the following section.

Measurement accuracy requires that the measurement be traceable to a defined or standard unit of measurement. This link is normally provided in the laboratory by secondary or working standards that are, in turn, related to the defining standard by a primary or reference standard. The two types of material standards in common use are line-spacing standards whose length is the distance between two engraved lines, and end standards or gauge blocks whose length is the distance between two optically-flat, parallel surfaces [26]. Since the meter has been defined in terms of the vacuum wavelength of monochromatic light of 605.6 nm from krypton 86 [27], all length measurements must ultimately be referenced to this defining standard by interferometry.

Interferometry is presently used to calibrate both line standards and end standards [28] at the NBS. Many research institutions and commercial firms engaged in some form of length measurement or manufacturing measurement equipment employ working standards calibrated on these NBS measurement systems. Some of the facilities also have mechanical comparators that use the NBS-calibrated scales or gauge blocks for making routine length measurements. For example, scales and micrometer stages, such as those used with the microscope for measurement purposes, are calibrated on these mechanical comparators. However, the NBS systems cannot be used to calibrate line widths; thus, no working standards for line-width measurements on photomasks are presently available.

In order to properly characterize the optical performance of a microscope, the type of illumination and the optical aberrations must be considered. Image formation in a microscope is much more complicated than in an instrument like a visual telescope because the object is not self-luminous in a microscope and must be illuminated with an auxiliary source [29]. Diffraction patterns arising from this auxiliary illumination occur in the object plane of the microscope. These patterns partly overlap causing light vibrations at adjacent points to be partially correlated in phase. In addition to this spatial correlation, there can exist a temporal correlation of light that depends on the spectral pass-band of the illumination; these light correlations are characterized by the spatial coherence and temporal coherence, respectively. For the extreme cases of coherent and incoherent light emerging from the object, the resolution limit for a microscope without optical aberrations depends only on the light wavelength and the numerical aperture of the objective. Most real microscopes are not free of optical aberrations, and the illumination is neither coherent or incoherent. Therefore, the general image quality, which includes the image structure for various object contrast ratios and sizes of detail approaching the resolution limit, is more useful in describing optical performance than a single value of resolution limit.

The optical quality of microscope measurement systems commonly used by the IC community does not vary significantly; in general, the aberrations are small and do not greatly limit image quality. The major variations in these systems are the types of sample illumination and the sample properties. Therefore, the effects of partial coherence of the imaging system appear to be primarily responsible for existing dimensional-measurement differences. Even before calibrated artifacts could be used in these measurement systems to determine the measurement accuracies, the effects of illumination on each imaging system would have to be thoroughly determined.

Although the scanning electron microscope (SEM) has significantly improved resolution compared to the optical microscope, micromeasurements with the SEM require a careful dimensional calibration over the field of view occupied by the object to be measured. The resolution is distinct from the accuracy and precision of measurements and does not inherently guarantee that either measurement accuracy or precision will be improved compared to optical-microscope measurements. Furthermore, calibrated scales or measurement artifacts for micrometer measurements in the SEM are not presently available.

A dimensional measurement technique [4, 30] of increasing interest that does not require either a calibrated scale or visual readings uses Fourier optics. In this approach, the object to be measured is illuminated by monochromatic light, and the resulting diffraction pattern is usually collected by a lens; this far-field diffraction pattern is the spatial Fourier transform of the object. In theory, the locations of the nulls and peaks and the relative intensities of this pattern can be analyzed to give the size of the object. In practice, the object should be simple and symmetrical, such as a slit or a wire, to avoid highly complicated diffraction patterns.

4.2.2. Edge Definition

The location of a physical edge for a line, window, or other geometrical pattern on a photomask or silicon die is primarily of interest for dimensional measurements, registration of several masks, or alignment of mask and wafer. There are specific problem areas associated with edge location for dimensional measurements that were not treated in the previous section on measurement of small dimensions and will, therefore, be presented in this section. In addition, the present discussion will bear directly on the following section which discusses photomask registration.

The major sources of difficulties encountered in determining the location of a physical edge may be grouped into the following three categories: (1) physical profile of the edge; (2) methods for observing the edge and recording the profile; and (3) criteria selected for defining the edge location. In general, photomask and IC manufacturers currently experience measurement difficulties resulting from all three sources. It should be noted that these problems are not unique to the IC industry. Long before the advent of IC technology, such problems had been encountered in microdensitometry, surface measurement, microphotography, and deposition of thin films. For example, microdensiometry is chiefly concerned with accurately recording the optical-density variation as a function of position in a photographic image which typically exhibits sharp density gradients or edges. Surface-roughness measurements using contact probes are frequently used to map out the surface profile of materials, and interferometry is traditionally used for step-height measurements of various thin films. Neither contact probe nor step-height interferometry are very applicable to locating a physical edge because these techniques have relatively poor resolution and accuracy in the sample plane or horizontal direction.

The physical profile of an edge in a photomask or IC die depends primarily on the type of material, such as chromium, iron oxide, silver-halide emulsion, or silicon oxide, and the process by which the edge was prepared. Over the past few years, efforts to produce IC patterns have resulted in the routine generation of physical edges that exhibit sharper profiles compared to those of the patterns produced by early techniques of microphotography. Included in recent efforts are improved contact printing techniques, development of special optics, use of hard-surface photomasks, and electron-beam processing. However, the majority of photomasks currently used are silver-halide emulsion and, therefore, the typical edge profile results from exposing adjacent regions of emulsion with high and low intensities of visible light. Even with the use of high resolution emulsions, diffraction-limited optics, intimate contact printing, and controlled processing, there are chemical-diffusion effects that occur during exposure of adjacent emulsion areas to high and low light levels [31] and, thereby degrade an originally sharp edge. One approach for producing sharper edges in emulsion is high-contrast processing or clipping [32]. This technique may lead to difficulties in controlling dimensional tolerances. Chromium on glass is grainless compared to emulsion and can provide a sharper edge. In addition, the photoresist coating used on a chromium photoplate does not exhibit a grey scale like silver-halide emulsion and, therefore, can provide sharper edges as in high-contrast printing. The IC die also contains silicon-oxide edges which are structurally different from the metallic and emulsion edges. In general, irregularities in both the horizontal and vertical dimensions of the edge are more pronounced for silicon oxide and make dimensional measurements more difficult.

The instruments generally used in the IC industry to observe and record the edge profile include optical microscopes, SEM's, and microdensitometers. The optical microscopes are used chiefly for dimensional measurements, mask and wafer alignment, and defect inspection. These observations are concerned with the location of the edge in the sample plane rather than the detailed height variation. With an optical microscope, an operator usually places a crosshair at the edge of the line or shears the line images until opposite edges just touch as in the filar or image-shearing eyepiece. In any event, the operator must make a visual judgment of the edge location; the edge location chosen can depend on the type of illumination, the light-scattering properties of the sample, and the experience of the operator. For example, an edge on an emulsion mask viewed under dark-field transmitted light appears as a bright line surrounded by a dark field, and the crosshair can be positioned symmetrically on the line; while under bright-field transmitted light, this edge appears at the opaque-transparent interface and symmetrical positioning of the crosshair is difficult. In photoelectric microscopes [33], which require essentially no visual judgement by the operator for determining the edge location, the optical image of the edge is converted to an electronic signal, and the edge location is based on a null signal or a slope-detection criterion. However, there exists no method for determining the relation of the edge location in this microscope system with the actual edge profile.

The SEM has been used to provide detailed examinations of edge profiles on photomasks, on IC dice, and in photoresist films [34, 35]. These studies have shown some of the edges to be highly irregular or jagged. These irregularities are a source of error for dimensional measurements and lead to significant light scattering with optical inspection techniques. Because of the high resolution of the SEM, it is one of the most promising techniques for determining the actual edge profile. Due to the cost, complexity, and sample preparation requirements, the SEM has thus far had limited use in the IC community.

Optical microdensitometers have been used to trace line-width profiles of both emulsion and hard-surface masks. Hard-surface masks, such as chromium, are highly reflective and can cause significant scattered light, or flare, in the microdensitometer; one investigator [36] has reported that as little as one percent flare light can degrade the image of an edge beyond the point where useful information can be obtained. Furthermore, since flare tends to be object dependent, the comparison of profile traces between hard-surface and emulsion edges on the same microdensitometer must be treated cautiously. In addition, current microdensitometers generally do not operate in a linear mode at the high spatial frequencies [37, 38] which often occur in the detail of the edge profile; this non-linear operation stems from the partial coherence of the illumination system and is essentially unavoidable, owing to the optical design of these systems. The degree of illumination coherence also affects the position and profile of the edge in image-forming systems such as microdensitometers and optical microscopes. A brief discussion of these effects is presented in appendix B.

There is presently no single criterion for edge definition that is equally applicable to different instruments and different types of samples. From the previous discussion, it is apparent that the selection of a criterion for edge location, such as half-power point or maximum slope, would be influenced by the available trace or record of the edge profile. For example, with edges scanned by a microdensitometer, a geometric average of the slopes of the output trace is the basis of the various measures of edge quality called acutance [39]. The measurement of acutance may prove too cumbersome for the detailed profile obtained from an SEM, particularly for a rough edge. Moreover, none of these techniques for determining edge location can be used with an optical microscope since it has a small depth of focus and normally does not provide much detail in the vertical direction.

4.2.3. Registration

In routine production, fabrication of a single IC device may require from four to twelve sequential mask layers. For a device series of masks, reqistration is defined [40, 41] as the accuracy of the relative positions of all functional patterns on any mask with the corresponding patterns of any other mask when the masks are properly superimposed. Registration is also sometimes used in the IC community to describe the accuracy of the relative position of a single geometric pattern on a mask with an existing pattern on a silicon wafer; however, in conforming with the recommended definitions of reference 40, this accuracy should be considered alignment rather than registration. Although techniques [6, 42, 43] for measuring mask registration are often a measure of mask and wafer alignment, this alignment is usually regarded as part of wafer processing rather than mask fabrication; therefore, in the present discussion, only those aspects of mask and wafer alignment that bear directly on mask registration will be presented.

Alignment marks are used on the mask reticle to permit rotational and translational alignment of the mask image preparatory for the step and repeat phase. Other alignment marks are used to position masks for registration check and to position the mask for wafer exposure. These alignment marks are often simple geometric forms such as straight bars, L-shaped bars, and crosses. For a reticle or a mask with a single pattern, the alignment marks are included in the artwork or produced by the automatic pattern generator and are located outside the functional pattern area; whereas, for the common multi-pattern mask, the marks are generated from a separate reticle and are located either within or outside of the pattern array. An example of alignment marks is shown in figure 1.

Mask registration and alignment of mask and wafer are generally checked by visual inspection through a comparison microscope that superimposes two image. These optical systems are often equipped with a micrometer stage, filar eyepiece, or image-shearing eyepiece to permit measurement of registration and alignment. In practice, a pair of masks is first observed under low magnification and the alignment marks are used to superimpose the two mask images; then, under higher magnification, a detail, such as a line width, for a pattern of one mask is compared with the corresponding pattern of the other mask. A measure of registration is the relative separation of these comparative pattern edges whenever these patterns are designed to overlap or just touch with no separation on the final wafer. Although this measurement of registration is a linear measurement in the usual comparative microscope, it should be noted that some registration errors are also described by an angular difference, such as array rotation or pattern rotation. In any event, this visual measurement is subject to some of the same optical limitations and dimensional errors discussed previously. For example, the accurate comparison of pattern geometry much below 1 μm is limited by the diffraction effects of light even with microscope optics that exhibit no aberrations. Furthermore, the effects of partial coherence on image formation and subsequent dimensional measurements will depend to a large extent upon the type of illumination and the optical properties of the mask. Therefore, some of the difficulties of locating the physical edge, as discussed earlier, are also encountered in checking mask registration.

In addition to optical limitations, most of the present equipment for determining registration has two basic shortcomings. First, this equipment compares only two masks at the same time and, consequently, it is not apparent from a registration-error measurement which mask has the pattern in the desired design location. Second, alignment of emulsion or chromium masks is difficult due to the opacity of the patterns. This difficulty led to the development of partially transparent, or see-through, masks such as iron oxide [44, 45] and silicon. Even with these see-through masks, considerable time is still spent by the instrument operator in aligning the masks before registration is measured.

The causes of registration errors include the following: (1) reticle misalignment and stage positional errors in the step-and-repeat camera; (2) non-flatness of mask substrate; and (3) environmental changes. The registration errors introduced by the step-and-repeat camera have attracted considerable attention since the early development of IC's. The primary reason for developing the multi-barrel step-and-repeat camera, which has separate optical systems for projecting more than one mask image on a common photoplate, was to eliminate registration errors introduced by non-repeating stage movement. However, recent experience has shown that multi-barrel instruments may introduce registration errors from variations between the separate optical systems; these differences include unmatched lenses and magnification differences, and alignment differences in the separate reticles. Furthermore, it is not always possible in actual production to produce masks that are all acceptable from one run on a multi-barrel system, particularly when the number of optical barrels is large. Thus, the defective masks have to be remade with some loss in registration tolerance. The current trend at some IC facilities with both single and multi-barrel equipment is to use the single-barrel configuration for high-quality masks requiring tight dimensional and registration tolerances.

During exposure of the sub-master and working mask, a bow or warp in the mask substrate often results in a registration error. If the non-flat glass substrate is temporarily flattened against the master as in vacuum contact printing, the pattern will be printed on a flat surface, but this sub-master will return to its previous curvature when released. Therefore, the spacing between patterns on the sub-master will vary from mask center to edge when compared to the pattern spacing on the master; this relative change of pattern spacing relative to the proper spacing is usually termed run-out or pitch error [40]. Furthermore, this type of error is often the major registration error resulting from the stepping errors discussed previously.

If a mask series is fabricated over a relatively long period of time, environment effects such as temperature variation can affect the dimensional stability of the mask substrate and results in registration errors. This effect can be particularly important if a replacement mask has to be made at a later time and is required to retrofit into the original mask series.

Present registration tolerances in the IC industry range from about ± 0.25 μm to ± 2.5 μm. In general, the precision of mask registration should be better than the minimum line width. As circuit density increases in the near future, the required registration tolerances will quite naturally become even more critical. The technology that must eventually replace visible radiation in the fabrication of masks with pattern geometry below 1 μm should also include a method to ensure better registration than presently available with optical equipment. One approach [9, 46] using an electron beam to generate masks also uses the electron beam to register masks automatically and to align mask and wafer automatically; results indicate a ± 0.2 μm alignment on 5.08-cm diameter silicon wafer. Another approach [47] that uses X-ray lithography in the fabrication of elastic surface-wave devices also suggests that X-ray detectors coupled with piezoelectric drives could be used to provide ± 0.1 μm registration precision; this system would also automatically align each mask during successive printing steps on the wafer.

5. CONCLUSIONS

The present study has identified the current optical and dimensional-measurement problems related to the fabrication and use of photomasks in semiconductor processing. These problems have been treated in detail in previous sections of this report and are summarized below.

5.1 Optics

(a) The majority of optical problems are directly related to dimensional-measurement problems through the optical instruments used to fabricate, inspect, and register photomasks; these problems are summarized in the next section on dimensional measurements.

(b) Although some optical systems have been designed specifically for the requirements of the IC industry, small-volume IC manufacturers cannot financially support the development of these special optics and cannot guarantee a sufficient market to assure the optics manufacturer the recovery of design and manufacturing costs. This often results in the use of off-the-shelf optics, thereby constituting a strong compromise in performance and cost.

(c) In general neither the supplier of optical systems, which are the basis of IC photolithography, nor the IC manufacturer uses optical testing such as interferometry to determine the imaging performance. Usually, the optical supplier furnishes only design data, prototype test data, or limited resolution-chart testing, and the user relies chiefly on the quality of the final IC device to assess the optical equipment.

(d) The pronounced diffraction effects resulting from illumination of submicrometer geometry with visible radiation constitute a basic limitation to the printing of acceptable patterns in photolithographic processing. Although this limitation is widely accepted by the IC community, a considerable effort is still made to print, inspect, and measure patterns with dimensions approaching the wavelength of light. This effort often involves a tight control of photographic processing parameters and improvement of the mechanical precision associated with processing equipment. The results appear to be very unrewarding to the IC manufacturer since the final acceptable devices are then produced on a costly best-effort basis.

5.2. Dimensional Measurements

(a) The major measurement problems are dimensional measurements below 10 μm, location of a physical edge for a line or other mask pattern, and mask registration; these problems routinely occur during the use of optical instruments used to fabricate, inspect, and register masks.

(b) Line-width measurements are the usual type of dimensional measurements made on masks. These measurements are made from left edge to right edge, or vice-versa. There are presently no measurement artifacts available for calibrating equipment used in line-width measurements. The NBS line-standard interferometer cannot be used to calibrate line-widths; thus, no working standards for line-width measurements on photomasks are currently available.

Significant differences occur between measurements made on the widely used image-shearing and filar eyepieces coupled to optical microscopes; the inability to determine measurement accuracy largely precludes the resolution of these differences. Consequently, photomask and IC manufacturers have concentrated their measurement efforts on dimensional repeatability of pattern geometry and have depended on the reliability of the final IC device rather than accurate comparison of pattern geometries to design data. As a consequence of such problems, the learning curve for device development and reliable production is longer than is desirable, and customers are frequently unable to obtain short runs of custom devices to meet special needs in an affordable way.

(c) Equipment manufacturers have significantly improved the mechanical precision of equipment used in mask fabrication and in the measurements of dimensions and registration. A few systems using interferometers have also improved the mechanical accuracy; since the dimensional accuracy of the resulting mask patterns and mask registration must still be determined by independent measurements, this accuracy remains undetermined.

(d) The type of illumination, such as reflected, bright-field, and dark-field, and its degree of coherence are known to affect significantly the apparent edge location in an optical measurement system such as the microscope. These effects, rather than lens aberrations, appear to be the prime limitations to measurement precision and interpreting measurement differences among various optical measurement systems.

(e) The difficulties associated with mask registration are primarily measurement inaccuracy, location of a physical edge, and the limited visibility resulting from a comparison of masks with opaque patterns. Even for masks with semi-transparent patterns, the measurement problems remain.

6. RECOMMENDATIONS

The following recommendations are made in view of the current optical and measurement needs in photomask technology that have been identified and discussed in the present report.

6.1. Optics

(a) The optical properties such as the pupil function, the optical transfer function, the presence of aberrations, the resolution, and the depth of focus of photolithographic optical equipment should be measured. These properties are measured by interferometric lens testing and specify the optical performance of the equipment. Since the quality of both photomask and IC devices is limited by the optical performance of photolithographic equipment, a knowledge of these properties would benefit the industry.

(b) An alternate approach to photolithography, such as electron-beam and X-ray lithography, should be developed for the routine processing of semiconductor devices with sub-micrometer geometry. In the interim, a conformable mask could be used in a printing system that provides uniform intimate contact over large areas in order to improve the quality of patterns with geometry from about 1 μm to 0.5 μm.

6.2. Dimensional Measurements

(a) A calibrated measurement artifact for determining accuracy of line-width measurements below 10 μm must be developed for use in the IC industry and all other areas concerned with micrometrology. Currently, the primary measurement need in the IC industry is for the high-volume devices with smallest geometry from about 2 μm to 5 μm that are measured with optical systems. Increasing demands for higher density, smaller geometry devices indicate a future need for dimensional measurements as small as 0.5 μm. Measurement artifacts or working standards must, of course, be traceable to the primary length standard (monochromatic radiation of wavelength 605.6 nm).

(b) The operating conditions and limitations of the optical microscope coupled with measurement eyepieces must be more thoroughly studied and developed. The effects of sample properties, types of illumination, and the degree of coherence on dimensional measurements must be included. Of particular interest to the IC industry, with its sizeable investment in various types of optical measuring equipment, would be a recommended set of practices to follow in obtaining measurements on a particular class of instruments under specified operating conditions. Using the measurement artifact in conjunction with the improved theory developed for the microscope would permit the measurement of small dimensions to a known accuracy.

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APPENDIX A

COMPARISON OF DIMENSIONAL MEASUREMENTS MADE WITH IMAGE-SHEARING AND FILAR EYEPIECES

BY

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Preliminary laboratory tests were made to investigate the measurement differences between an image-shearing eyepiece and a filar, or micrometer, eyepiece. The objects measured were a nominally 15-μm diameter tungsten wire and a nominally 10-μm diameter pinhole which were the only suitable artifacts immediately available. The two objects were illuminated both by transmitted light (bright field) and by reflected light (dark field) from an incandescent source. A helium-neon laser was used as a source for transmitted coherent illumination. In the present tests, the use of laser for reflected illumination resulted in numerous fringe patterns across the microscope field of view. These fringes arose from scattering and multiple reflections in the condenser and resulted in significantly degraded image quality; thus, measurements were not made with reflected laser illumination. Dimensional calibrations were made against a stage micrometer calibrated by the National Bureau of Standards.

The results of the dimensional measurements for both objects and both types of microscope eyepieces are given in table 1. Measurements of the wire diameter with the filar eyepiece in white light gave slightly larger dimensions than corresponding measurements made with the image-shearing eyepiece for both reflected white light and transmitted laser light; larger dimensions were measured with the image-shearing eyepiece for transmitted white light. Measurements of the pinhole diameter showed the filar eyepiece to give larger dimensions than the image-shearing eyepiece with transmitted white light and laser illumination. The image-shearing eyepiece gave larger dimensions than the filar eyepiece with reflected white light.

These measurements are not representative of the measurements the IC community is currently making on photomasks. These samples differ from photomask patterns especially in the height dimension which is much greater than that on photomasks.

A comparison of linewidth measurements using both eyepieces was made on nominally 12-μm width chromium lines on a glass substrate which more recently became available. The results shown in table 2 are the average values of twenty measurements of each line width. These values show a difference of 0.11 μm between the filar and image-shearing for bright field; this difference is within the 3σ value, while for dark-field the difference of 0.77 μm is far greater than the 3σ value. If the bright-field and dark-field measurements are compared for the same type of eyepiece, a significant difference exists for the filar. No explanation of these differences has been formulated, but such discrepancies are typical of those currently found for measurements of these dimensions in the photomask and IC industry.

Table 1: Dimensional measurements of wire width and pinhole diameter using filar and image-shearing eyepieces on an optical microscope.

a. Measurements for a nominally 15-μm width wire.

	Filar (μm)		Image-Shearing (μm)	
	White light	Laser	White light	Laser
Reflected	14.94	---	14.70	---
Transmitted	15.12	16.2	16.45	15.8

b. Measurements for a nominally 10-μm diameter pinhole.

	Filar (μm)		Image-Shearing (μm)	
	White light	Laser	White light	Laser
Reflected	9.72	---	10.00	---
Transmitted	10.37	10.22	9.15	9.20

Table 2: Comparison of dimensional measurements for a nominally 12-μm width chromium-on-glass line (486-nm illumination); 3σ value for each measurement is approximately 0.25 μm.

	Filar (μm)	Image-Shearing (μm)
Bright Field	11.76	11.87
Dark Field	11.06	11.83

APPENDIX B

EFFECTS OF ILLUMINATION COHERENCE ON APPARENT EDGE POSITION IN OPTICAL-IMAGING SYSTEMS

By

Richard E. Swing

When viewing objects with discontinuities such as sharp edges and well-defined lines in the microscope, it is possible to make incorrect measurements of their dimensions because of the partial coherence of the illumination. Indeed, the observational device does not need to be a microscope; a microdensitometer, for example, employs microscope optics and displays the scanned image as a chart-trace or magnetic-tape record. If widths of lines or locations of edges are based on the location of the half-power point (the mean between maximum and minimum image transmittance), the degree of partial coherence of the illuminating system can cause serious errors in the results.

These effects were reported by P. S. Considine [48]; his report is an experimental summary based on the theoretical considerations of a doctoral dissertation by T. J. Skinner [49]. In the summary by Considine, it is shown that if the edge discontinuity is located at the half-intensity point, the coherent image of the edge is shifted by

$$D = \frac{0.106\ \lambda m}{N.A.} ,$$

where m is the magnification, N.A. is the numerical aperture of the objective lens, and λ is the illumination wavelength; it is assumed that an ocular is not used in combination with the objective (for an ocular, the value of m is increased). The significance of D is shown in figure 3. For example, let

$$N.A. = 0.25,\ m = 10X,\ \lambda = 500\ \text{nm};$$

thus, $$D = \frac{(.106)\ (10)\ (.5)}{(.25)} = 2.12\ \mu m \simeq 2\ \mu m .$$

This 2-μm shift of the image is equivalent to a 0.2-μm shift of the object, i.e., the object shift is the image shift divided by the magnification or D/m. Even if the optics are improved by going to a 0.65 numerical aperture (with a consequent increase in magnification to 20X), D is 1.6 μm or still about 2 μm. Thus, there is an error associated with measuring the image at the half-power point if the illumination is fully coherent. Since the illumination in a microscope system is usually partially coherent, the error is between zero and the value of D. Unless the degree of partial coherence is known, the error is only bracketed. It would be less ambiguous to illuminate with completely coherent light and calculate the edge location at the quarter-intensity point (where the edge will be found in such illumination).

The Considine summary considered only edges. These edges can be treated in isolation and do not interact with any other image structure. Skinner, in his dissertation, treated the problem of lines and found that when the line widths were greater than about ten times the width of the impulse response of the imaging optics, the line could be treated as the combination of two edges whose effects did not interact. As an example, consider an f/1.6 lens, such as these used in high-quality step-and-repeat cameras, to be diffraction limited for actinic radiation of 405 nm. The impulse response for this lens is 1.3 μm; therefore, the line width that images without interaction between its two edges is approximately 13 μm or greater. A detailed analysis for line widths below such values must be carried out before the assessment of the effects of partial coherence on line-width measurements can be made.

Recent research [60] indicates that with an image-splitting eyepiece the measurement of line widths can be accurate to better than one tenth of the smallest resolvable dimension. For this accuracy, it is assumed that the object is incoherently illuminated. This accuracy may not be realized in practice because of the inability to incoherently illuminate the object as indicated in the study of tri-bar target imagery by D. N. Grimes [51]. The program needs an investigation with considerable attention given to microscope adjustments and to the effects of partial coherence relative to the object structure.

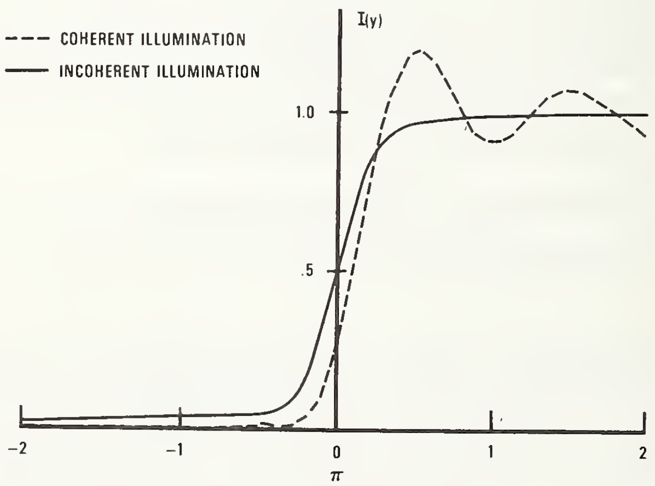

Figure 3. Theoretical plot of the intensity distribution for a coherent and incoherent image of an edge. (Philip S. Considine, Journal of the Optical Society of America, Vol. 56, p. 1003, 1966.) Note - The abscissa is proportional to the horizontal distance from the edge. The horizontal distance between the two curves at the half-power point represents an edge image displacement of about 2 μm for the examples of appendix B.

APPENDIX C

SELECTED BIBLIOGRAPHY OF PHOTOMASK PUBLICATIONS

The literature sources cited in this bibliography contain information related to the optical and micrometrological aspects of the manufacture and use of photomasks in semiconductor processing. This listing contains book chapters and sections, articles from technical journals, contract reports, reports by U.S. Government agencies, company publications, and proceedings of technical conferences, seminars, and symposia. Publications that describe complete procedures for fabrication of a specific IC device and only briefly describe photomask procedures or publications that concentrate primarily on other aspect of photomask technology, such as art-work generation, photoresists, or defect inspection, have generally not been included It should also be noted that references to electron-beam and x-ray generation of masks are excluded since the present study was concerned primarily with masks made using visible and ultraviolet radiation (photolithography).

The approximate period covered by the bibliography is from January 1966 through November 1974 and the arrangement is chronological. Some of these literature sources are also cited as references in the present report. The abbreviations used for technical journals follow the recommendations of (1) ACCESS - Key to the Source Literature of the Chemical Sciences (The American Chemical Society, 1969) and (2) Publications Indexed for Engineering (Engineering Index, Inc., New York, 1974).

Some of the bibliographic sources are also available directly from NTIS (National Technical Information Service, 5285 Port Road, Springfield, Va. 22151) and DDC (Defense Documentation Center, Cameron Station, Alexandria, Va. 22314).

The ASTM documents referenced are available as separate reprints from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103. These documents appear in the 1974 edition of the Annual Book of ASTM Standards in essentially the same form as Tentatives.

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. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Photomasks are the basic artifacts for transferring design geometry to the semiconductor wafer in integrated circuit (IC) production. Currently, photolithographic techniques using optical equipment are the primary means for both fabricating masks and using masks to print patterns on wafers. The present study was to identify the major optical and dimensional-measurement problems related to the fabrication and use of masks.

The results show that the primary optical problems are those related directly to the use of optical instruments for dimensional measurements of IC pattern geometry. Furthermore, most suppliers and users of optical equipment for mask fabrication do not conduct sufficient optical testing to determine imaging performance. The basic limitations derived from light diffraction and coherence continue to limit the quality of masks and IC devices with sub-micrometre geometry, and acceptable units are produced generally on a best-effort basis. The primary dimensional-measurement problems are (1) accurate measurements below about 10 μm, (2) edge definition or location of a physical edge for a line, and (3) mask registration. Recommendations to improve the accuracy of dimensional measurements are given.

A bibliography of publications related to the optical and micrometrological aspects of photomasking is included.

KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Integrated circuits; microelectronics; micrometrology; photolithography; photomask; semiconductor technology.

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